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Infrared Optoelectronic Volumetry, the Ideal Way to Measure Limb Volume

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Objectives: *The aim of the study was to compare a novel infrared optoelectronic system (Perometer) of limb volume measurement with water displacement and two indirect measurement techniques.*
Design: *A prospective experimental study.*
Methods: *In 10 healthy male volunteers (20 limbs) we compared limb volume measurements obtained by water displacement, infrared perometry, the disc model method and the frustrum method. In a further 17 patients with swollen limbs due to lymphatic (9 limbs) or venous (11 limbs) disease, perometry was compared to the disc model method and the frustrum method only.*
Results: *In normal limbs, mean ± S.D. limb volume using water displacement was 1802 ± 268 ml. Perometer values agreed almost exactly (1809 ± 262 ml, r = 0.97, variation ± 7% by limits of agreement) but both the disc (1923 ± 306 ml, r = 0.90, variation ± 14%) and frustrum (1905 ± 372 ml, r = 0.72, variation ± 28%) methods significantly overestimated limb volumes (p < 0.05 (ANOVA, Fisher's Least Significant Difference). In diseased limbs perometer, disc method and frustrum method results were 2415 ± 995 ml, 2494 ± 969 ml, and 2413 ± 870 ml representing variation of ± 17% and ± 23% for disc method and frustrum method respectively compared to perometry.*
Conclusions: *Perometry is a novel, extremely accurate and easy method for assessing limb volume. It provides more accurate results than traditional indirect measurement of limb volume and potentially is a very useful clinical and research tool.*

Key Words: Limb volume; Water displacement; Limb swelling; Perometer.

Introduction

Although limb swelling is a common clinical problem among orthopaedic and vascular patients, reliable measurement of limb volume is difficult. The "gold standard" for limb volume measurement, the water displacement technique, is based on the principle discovered by Archimedes over 2000 years ago. Although water displacement is a sensitive and accurate method of limb volume measurement,[1,2] it is time consuming, cumbersome and unsuitable for patients in the early postoperative period or in those with open wounds.

Several indirect methods of limb volume measurement have been described including the disc and frustrum methods.[3–5] Various measurements of the leg are taken, certain assumptions about the shape of the leg are made, and the volume is calculated by applying a mathematical formula. Although such indirect methods are reasonably accurate, they are operator dependant and time consuming.[1] The perometer is an optoelectronic system which uses infrared beams to measures the limb and calculates the volume electronically. This is certainly faster may be more convenient to use than existing methods but it is unclear how it compares to other methods of limb volume measurement. Thus the aim of the present study was to assess the reliability of infrared perometry in comparison to other methods of limb volume measurement.

Materials and Methods

Limb volume was studied in two groups of patients. Measurements in both groups were made under standard conditions — the subjects did not engage in strenuous physical activity prior to the test and all rested on a couch with the leg elevated to the level of the hip for 15 min prior to measurements being taken.

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In the first part of the study, the volume of each leg of 10 healthy male volunteers (n = 20) was measured using four different techniques. The volume of each limb between reference points marked on the leg at 3 cm below the medial gap of the knee joint and 3 cm above the tip of the medial malleolus was measured in random order using water displacement, perometry, the disc method and the frustrum method. In each case the average of three measurements was taken as limb volume. In the second part of the study, the volume of a diseased limb was measured in 20 limbs of 17 patients with either chronic venous or chronic lymphatic disease. The volume of both lower limbs was measured in three patients with bilateral disease. The distribution of these patients and their disease type is shown in Table 1. As all of these patients had ulceration or skin problems their legs were not immersed and volume was determined using perometry, the disc and frustrum methods only.

Water displacement

A specially constructed perspex tank was used to measure limb volume by water displacement. The tank was equipped with two overflow tubes and filled to the level of the lower one of these with water at 29°C (the approximate skin temperature of the leg and ankle). The lower overflow tube was closed and the patient's leg immersed in the tank up to the level of the marked upper reference point. When the displaced water reached the open upper overflow tube, the excess spilled into a 1000 ml graduated cylinder. The water was collected until the drop rate fell below one drop per second and the volume was recorded. The leg was removed, the tank refilled to the level of the lower overflow tube and this outlet was opened. The ankle and foot were immersed to the level of the lower reference point. The volume of water displaced into the graduated cylinder, equal to the ankle and foot, was subtracted from the total to give the volume of the leg alone. The technique was repeated on three occasions and the average of these three measurements was taken as leg volume.

Table 1. Patients with diseased limbs.

Disorder	Grade	No. of patients
Venous	I	1
Venous	II	4*
Venous	III	5*
Venous	Acute DVT	1
Lymphatic	II	2*
Lymphatic	III	2
Lymphatic	IV	5

*Among the 17 patients with diseased limbs, three had bilateral disease and both limbs were measured seperately. One patient had bilateral lymphoedema grade II; one had bilateral chronic venous disease grade III and one had bilateral venous disease, grade II on one side and grade III on the other.

Perometer

The perometer is illustrated in Fig. 1. The patients sits with the heel supported. The leg passes through a four-sided rigid plastic frame, free to move along a rail in the long axis of the limb. The frame bears two arrays of infrared emitting diodes at right angles to each other are along adjacent sides of the frame and two arrays of infrared detecting diodes opposite these. Each light emitter emits a frequency modulated narrow beam of infrared light to which three detectors only are sensitive; one immediately opposite the emitter and one on either side. Thus, each detector receives a signal from three emitters but can distinguish each signal by the modulation. As the frame is moved along the leg, the path of these beams is interrupted by the limb and the dimensions (in the x- and y-axes) are measured to an accuracy of 10^{-4}m. Sensors continuously determine the position of the frame along the leg (the z-axis). Markers placed on the leg allow identification of the upper and lower reference points. The data is passed directly to a personal computer and a three-dimensional image of the leg is generated. Limb volume between the reference points is then calculated from these dimensions using a modification of the disc method. This degree of accuracy renders the Perometer particularly suitable for use in a research setting.

Disc model method

To calculate limb volume using the disc method, the patients lies or sits on a couch with the leg resting on a graduated device marked at 3 cm intervals. The leg is divided into 3 cm discs between the reference points at knee and ankle and the circumference of each disc between the upper and lower reference points is determined. The volume of each disc is calculated according to a simple formula, $(C^2/4\pi)h$, where C = the circumference of the disc and h = the height of the disk. The volume of the leg is simply the sum of the volume of the individual discs:[4]

$$\sum_{i=1}^{n}((C^2_i/4\Pi)h)$$

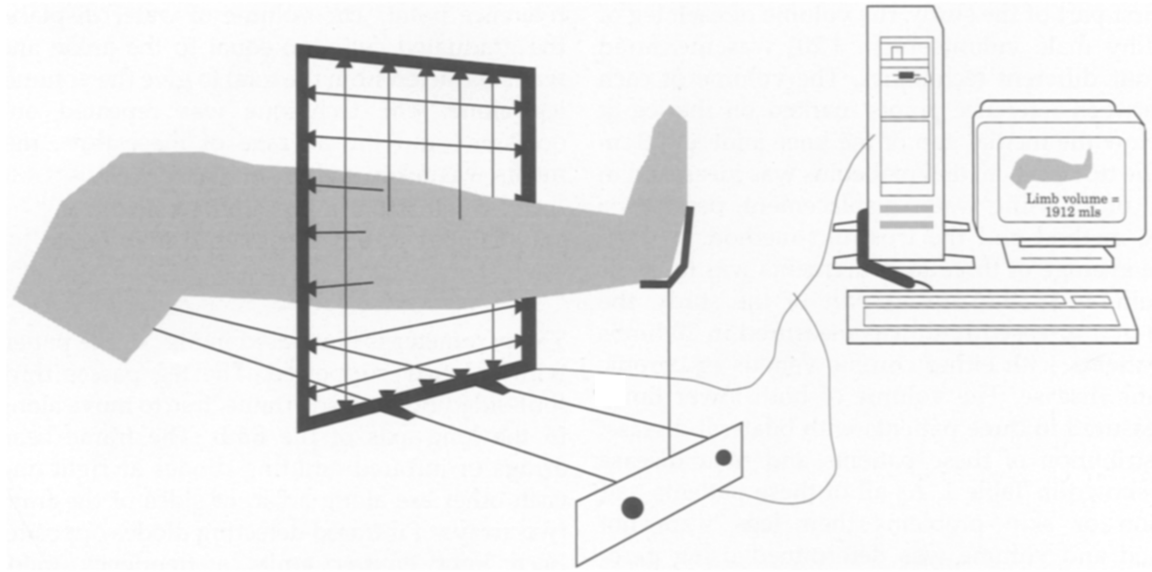

Fig. 1. The perometer consists of a frame bearing infrared detectors and emitters which is free to move along the rail. The patients leg passes through the frame and, as the frame moves up along the leg, the infrared beams are interrupted and the dimensions determined electronically.

Frustrum method

The Frustrum method is based on the assumption that the leg approximates in shape to a truncated cone or frustrum.[6] The volume of a frustrum can be calculated by measuring the circumference at the upper (*C*) and lower (*c*) reference points, the distance between these points (*h*), and applying these to the formula:

$$\frac{\Pi}{12\Pi^2}h(C^2 + Cc + c^2)$$

As inconsistency in tape measure tension can alter apparent limb circumference by up to 3%,[7] measurements in the disc and frustrum method were made using a spring-loaded controlled tension device so that the tape lay in close contact with the skin but did not unduly compress the underlying tissue. to avoid observer bias, all of the measurements were taken by a trained physiotherapist unaware of limb volume as determined by the other techniques and calculations were performed after all measurements had been taken.

Results are expressed as mean ± S.D. Limb volume was compared between the methods using ANOVA and Fisher's Least Significant Difference. Correlation between different methods was compared using Pearson's correlation coefficients and the level of agreement using the limits of agreement technique.[8] A p value of < 0.05 was regarded as significant. Ethical approval of the study was granted by the ethics committee of the Hammersmith Hospital.

Results

Mean limb volume values (± S.D.) for normal volunteers using each of the techniques are shown in Table 2. Of all of the methods, the perometer agreed most closely with water displacement. The indirect methods tended to overestimate limb volume, and this difference was statistically significant ($p < 0.05$, ANOVA and Fisher's Least Significant Difference) when compared to both water displacement and perometry. The difference between the techniques tends to be obscured by the normal variability in the population when looking at mean limb volumes. Thus, the mean absolute percentage measuring error illustrates the absolute difference between water displacement and each of the other techniques in individual limbs as a percentage of the total volume. This illustrates the close agreement between the perometer and water displacement, from which it varied by only 3%. In contrast, the indirect techniques

Table 2. Limb volumes in normal and diseased limbs comparing different techniques.

Method	Normal limbs ml (S.D.)	Diseased limbs ml (S.D.)
Water displacement	1802 (268)	
Perometer	1809 (262)	2415 (995)
Disc method	1923 (306)*†	2494 (969)
Frustrum method	1905 (372)*†	2413 (870)

*p<0.05 vs. water displacement.
†p<0.05 vs. perometer (ANOVA, Fisher's Least Significant Difference).

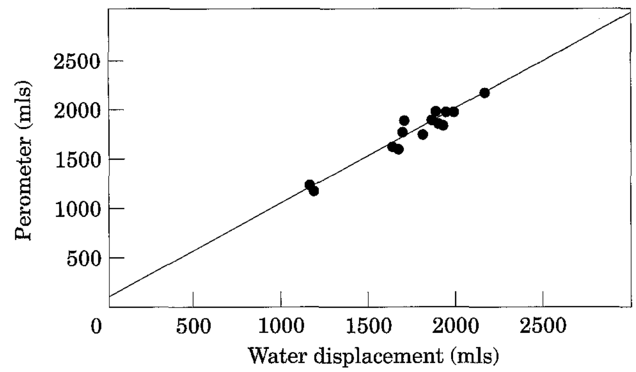

Fig. 2. Water displacement vs. perometer. Pearson's correlation coefficient (r) = 0.97. $p < 0.00001$.

differed from water displacement by 8% (disc method) and 12% (frustrum method).

Linear regression and calculation of correlation coefficients show a highly statistically significant association between each of the techniques and water displacement (Figs. 2–4). Among the three techniques, perometry agreed most closely with water displacement (Pearson's correlation coefficient (r) = 0.97, $p < 0.000001$). However, both the disc method (r = 0.90, $p < 0.000001$) and the frustrum method (r = 0.72, $p < 0.001$) also correlated quite strongly with water displacement.

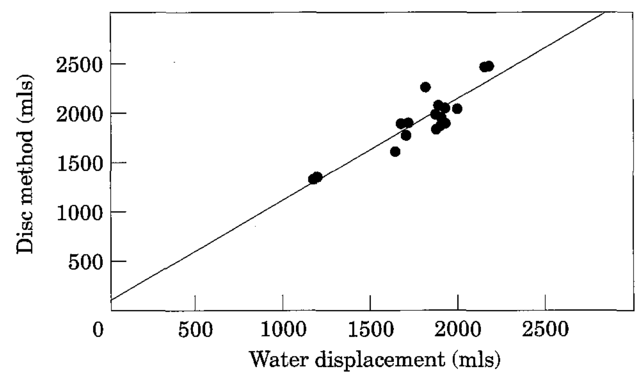

Fig. 3. Water displacement vs. Disc method. Pearson's correlation coefficient (r) = 0.90. $p$lt0.00001.

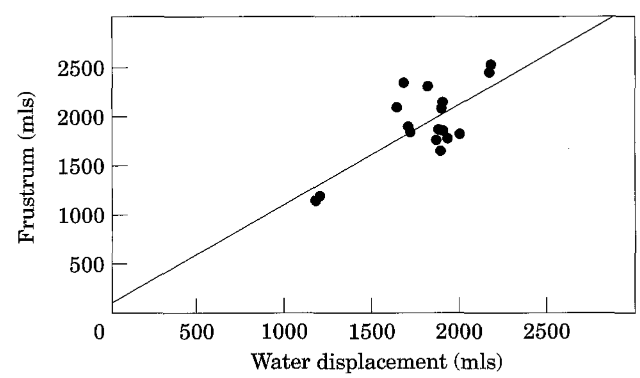

Fig. 4. Water displacement vs. frustrum method. Pearson's correlation coefficient (r) = 0.72. $p < 0.001$.

Bland and Altman have demonstrated that linear regression and correlation coefficients are unsuitable for comparing agreement between various measuring techniques and recommend instead the limits of agreement technique.[8] In this technique, the difference between measurements (d) made using each of the different techniques is plotted against their mean. Confidence intervals may be calculated from the mean difference (d) and standard deviation (S.D.) (d ± 2S.D.) and 90% of measured values will fall between these limits.

Applying this technique to the data, the graph in Fig. 5 was constructed. Limb volume, as determined using the perometer, fell within confidence intervals of –141 ml and + 126 ml compared to water displacement values representing only a variation of ±7%. In contrast, confidence intervals for the disc method (as compared to water displacement) were –390 ml and + 147 ml representing a variation of ±14%. The widest variability was seen in the frustrum method where the confidence intervals were –621 ml and + 416 ml, and, thus, these values varied by ±28% from water displacement.

Mean limb volume for the 20 patients with diseased limbs was also calculated and the values are also shown in Table 2. Limb volume agreement between the methods was closer than in normal limbs. Linear regression and calculation of correlation coefficients showed close correlation between the disc and frustrum methods and the perometer (disc method r = 97, $p < 0.00001$; frustrum method r = 0.95, $p < 0.001$). Although both mean limb volume measurement and correlation coefficients suggest closer agreement between the techniques, the limits of agreement (Fig. 6) compared to the perometer were –484 ml and

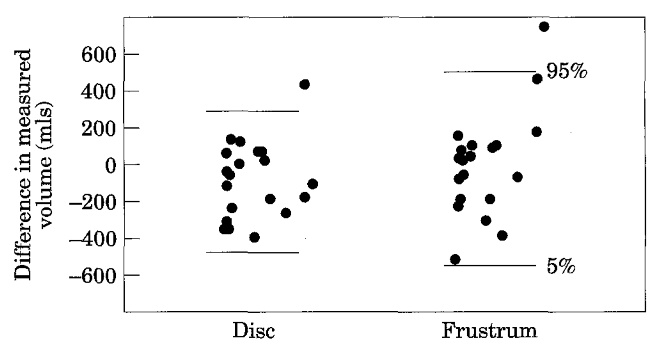

Fig. 5. Limits of agreement test applied to volumes obtained in normal limbs. Individual data points and 5% and 95% confidence intervals are shown.

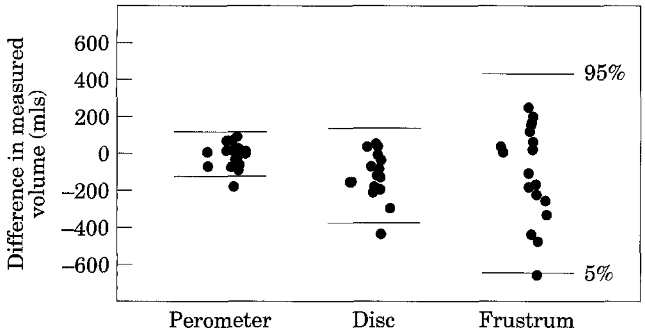

Fig. 6. Limits of agreement test applied to volumes obtained in diseased limbs. Individual data points and 5% and 95% confidence intervals are shown.

+ 326 ml (variation of ± 17%) for the disc method, and −547 ml and + 550 ml (a variation of 23%) for the frustrum method.

Discussion

This study was designed to compare existing direct and indirect methods for the measurement of limb volume with perometry, a novel method which uses modern optoelectronic infrared technology to measure limb dimensions. Limb volume, as measured using the perometer, correlated very closely with water displacement volumes in normal limbs. Although the indirect techniques also correlate quite closely with water displacement, the limits of agreement data suggest that the perometer may even be superior to indirect measuring techniques in the assessment of the volume of the normal limb. The results in diseased limbs suggest that the perometer may have a clinical application in the quantification of limb swelling.

The accurate determination of limb volume and the change in volume over time is crucial in assessing the response to treatment of patients with limb swelling due to lymphatic and vascular disease, or following trauma or elective surgery. However, none of the existing techniques for measuring limb volume are ideal. Although water displacement is accurate and continues to be used as the "gold standard" measurement, there are several problems with this technique. Filling the water bath, allowing it time to equilibrate and changing the water between patients to prevent cross-infection renders the technique very time consuming. The problem of water immersion of limbs with dressed wounds further limits the routine clinical application of this method.

Indirect methods, including the disc method and the frustrum method as used in this study, have the advantage of requiring minimal technology and thus being easy to perform. However, they are time consuming and operator dependent. Furthermore, the frustrum method depends on certain assumptions about the shape of the limb that may vary between individuals or between health and disease. The accuracy of the frustrum method may be maximised by using the circumference of the limb measured at the widest and narrowest points as the shape of that segment of the leg will most closely approximate to a frustrum. However, in these circumstances, the techniques does not measure the volume of the whole leg making it difficult to compare with other techniques. This approach also renders it difficult to apply the frustrum method in monitoring changes in the volume of diseased limbs over time where limb shape may vary as a function of either the disease process or the treatment.

Accordingly, fixed reference points at which all measurement were taken were used in this study as described by other authors that compare different techniques.[1] The use of fixed reference points may compromise the accuracy of the frustrum method because the segment being measured is not necessarily a true frustrum, but facilitate comparison to other techniques. Using these criteria, previous studies of these techniques have found the disk method to be accurate but have concluded that the frustrum method is too imprecise for clinical use.[14] The present study supports the conclusions of other authors that the disk method is reasonably accurate and thus useful for routine clinical assessment while adding to their doubts about the applicability of the frustrum method.[1] Although mean limb volume data suggest that perometry correlates more closely with the frustrum method in diseased than in normal limbs, the limits of agreement data demonstrate that the actual agreement is no closer than in normal limbs.

The perometer measures limb dimensions in a matter of seconds to a high degree of accuracy. The present study demonstrates that perometry is highly accurate in measuring the volume of the normal limb and suggests that perometry will be clinically useful in the assessment of diseased limbs. Further linear studies of volume change are required to assess the reliability of the perometer over time. The perometer may have further application as a volume plethysmograph because it allows changes in either whole limb volume or the volume of any individual disc to be monitored in real time. As a plethysmograph it would have the distinct advantage of allowing limb volume measurement without making contact with the limb and of having zero compliance.

In conclusion, this study has demonstrated that a novel optoelectronic device for the non-invasive determination of limb volume, the perometer is as accurate as the current "gold standard", the water plethysmograph, and more accurate than indirect methods based on limb measurement in normal limbs. These results also suggest that the device will satisfactorily measure limb volume in diseased limbs and indicate that the perometer may become a useful adjunct in the determination of limb volume and thus in the assessment of limb swelling in both research and clinical settings.

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